Performance of a Low-Luminosity Low Energy Neutrino Factory

E. Christensen, P. Coloma, P. Huber, and the MASS working group of the Muon Accelerator Program

A Neutrino Factory (NF) is recognized as the ultimate tool in precision neutrino oscillation physics [1]. In its current baseline configuration as proposed by the IDS-NF [2] it requires a 4 MW proton driver at a few GeV and the associated 4 MW target station and muon cooling, which in turn delivers 10^{21} useful muon decays at 10 GeV per 10^7 s and polarity. The detector is a 100 kt magnetized iron calorimeter at a distance of 2000 km. The combination of high powered beam and muon cooling renders a full scale NF a challenging accelerator project with the need for a significant R&D program.

Here we propose to consider a low energy, low luminosity version of a NF (L3NF), where the key to maintain the physics performance is to also include the so-called platinum channel, *i.e.* the appearance of ν_e and $\bar{\nu}_e$. The low muon energy of 5 GeV allows to reduce the baseline to 1 300 km in order to fully benefit from the, by then existing, 10 kt LAr detector in Homestake, which for the L3NF should be located underground due to the large duty factor of stored muon beams. The flavor composition of a NF beam requires charge identification of the lepton produced in the far detector, which is achieved by the addition of a magnetic field at the level of 0.5 T to the LAr detector, see Ref. [3]. The same detector configuration will potentially allow to detect the platinum channel with high efficiency and reasonable purity. For details of the detector implementation, see Ref. [4].

The fact that θ_{13} is large [5] allows a reduction in the overall statistics requirements by a large factor. Compared to the IDS-NF baseline, the detector size is reduced by a factor 10. To illustrate the impact of a reduced luminosity, consider the following scenario, based on back of the envelope scaling: using the *existing* Fermilab proton beam from the Main Injector with a beam power of 700 kW and a beam energy of 60-120 GeV would result in a factor of 10 reduction of luminosity – a factor of ~ 5 from the beam power and factor of 2 from the reduced pion production efficiency at higher beam energy. If we assume no cooling of the muon beam, another factor of 2 loss of luminosity is incurred. In contrast to the IDS-NF baseline assumptions, we assume an annual operation time of 2×10^7 s, a standard assumption for Fermilab experiments, as opposed to 10^7. As a result we obtain 10^{20} useful muon decays per polarity and year. Note that this performance is based entirely on existing technology and does not assume major upgrades to the Fermilab proton beam infrastructure.

Fig. 1 shows the results for the CP Violation (CPV) discovery potential of the facility, defined as the ability of the experiment to rule the CP conservation hypothesis ($\delta = 0, \pi$) at a certain confidence level (1 d.o.f.), assuming the mass hierarchy is unknown. The significance is shown as a function of the true value of δ. For reference, we also show the results for the LBNE experiment aimed at a 10 kton LAr detector, simulated according to the CDR from October 2012, Ref. [6]. As can be seen from the figure, the gain in performance is significant when information from all available channels is combined. The experiment would reach the 3σ level in a 30% to 40% of the available parameter space, depending on the performance of the detector.

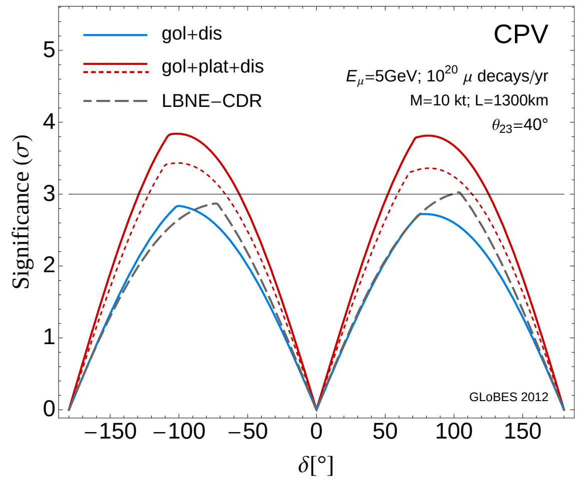

FIG. 1. Ability to exclude the CP conservation hypothesis. The statistical significance is shown as a function of δ, in the case when only the golden and disappearance channels are included in the analysis (blue lines, "gol+dis"), as well as when the platinum channel is also considered (red lines, "gol+dis+plat"). Dotted red lines show the results for the TASD-like detector performabce, while solid lines refer to LAr-like performance. For reference, the results for the preferred reconfiguration option for LBNE are also shown (gray dashed lines).

A similar performance gain is found for the mass hierarchy discovery potential and the precision in the determination of the CP phase, see Ref. [4].

The performance of the proposed low luminosity variant of the NF is based on what could be achieved with beams that can be provided by the current Fermilab accelerator complex. Nevertheless, further performance improvements would be realized with the availability of Project X [7] beams. The U.S. Muon Accelerator Program (MAP) is presently evaluating a staged approach which would take advantage of the beams planned for the early stages of the Project X implementation [8]. Such an approach is consistent with the accelerator upgrade path proposed for Fermilab. Ultimately a 4 MW, 8 GeV proton beam from Project X, muon cooling and an increased detector mass (by a factor of 1-3) would provide a facility with performance that matches or exceeds the baseline IDS-NF design.

[1] A. Bandyopadhyay *et al.* (ISS Physics Working Group), Rept. Prog. Phys. **72**, 106201 (2009), arXiv:0710.4947 [hep-ph].

[2] S. Choubey *et al.* (IDS-NF Collaboration)(2011), arXiv:1112.2853 [hep-ex].

[3] A. D. Bross, M. Ellis, S. Geer, O. Mena, and S. Pascoli, Phys.Rev. **D77**, 093012 (2008), arXiv:0709.3889 [hep-ph].

[4] E. Christensen, P. Coloma, and P. Huber(2013), arXiv:1301.7727.

[5] F. An *et al.* (DAYA-BAY Collaboration), Phys.Rev.Lett. **108**, 171803 (2012), arXiv:1203.1669 [hep-ex].

[6] LBNE Conceptual Design Report from Oct 2012, volume 1, `http://lbne.fnal.gov/papers.shtml`.

[7] Project X – Reference Design Report, V1.0, November 1, 2010, `http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=776`.

[8] Muon Accelerator Program Snowmass Whitepaper, in preparation, 2013.